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## MACROSTRUCTURE OF FRICTION STIR WELDS

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### **ABSTRACT**

This paper will discuss two of the well known large scale features of friction stir welds: the "onion rings" seen in transverse sections, and the striations on the surface of the work piece. It will be shown that the surface features (sometimes called "tool marks") are the result of irregularities on the rotating shoulder of the pin tool and disappear when the shoulder is polished. The "onion ring" structure seen in transverse cross sections is formed by parts of the "carousel", the zone of material adjacent to and rotating with the pin tool, that are shed off in each rotation. The relation between the carousel and the "ring vortex", a rotational flow extending both in and out of the carousel and resembling a smoke-ring with the hole centered on the pin tool, will be discussed.

### **INTRODUCTION**

Friction stir welding<sup>1</sup> is certainly the most interesting development in the field of welding in the past decade. From a technological standpoint, the technique has already found many uses in the aerospace field and others will certainly follow. From a purely theoretical standpoint, many questions of material flow remain unsolved leading to trial

Sato<sup>5</sup> and coworkers have used Orientational Imaging Microscopy to study the texture of grains in the weld zone of 6063 aluminum and note a predominant texture due to shear parallel to the pin surface which is consistent with the carousel that rotates with the pin.

Images of welds on clear polycarbonate samples<sup>6</sup> have shown that material can circulate around the pin and build up for more than one revolution until it is shed off into the wake of the weld. It is not clear, however, whether the material forms the same bulging sheets which give rise to the onion rings seen on aluminum samples.

From welds on bimetallic samples, Guerra<sup>3</sup> notes that there is transport of material from top to bottom of welds indicating that superimposed on this rotational motion around the pin is a vertical motion of material driven by the threads. This motion must turn to a rotational or vortex motion because volume must be conserved and the metal flow has no place to go but around. On the assumption that this vortex flow is symmetrical around the pin, the vortex takes the form of a ring with the pin in the central hole. Distortion of the metal outside the recrystallized weld zone and tracer displacement observations<sup>7</sup> can be interpreted as an effect of the ring vortex and thus are visible evidence for the ring vortex. This ring vortex flow is downward in the wash of the threads near the center of the weld, outward near the bottom and, to conserve volume, upwards at the edge of the weld and inwards toward the pin at the top of the weld. Fig. 1 shows the rotational carousel motion and the ring vortex motion. An element of material near the pin at the front of the weld undergoes circular motion around the pin while descending in a helix until it exits the carousel near the root of the weld and ascends in the ring vortex flow. Depending on the rotational speed and weld velocity, the inward

and error work on pin tool shape and other welding parameters. Accordingly, this paper will discuss two readily visible phenomena seen on friction stir welds: the “onion rings” seen on transverse sections and the surface striations or tool marks that exist along the weld path. The origin and size of these rings will be discussed in terms of the zone of material that surrounds and rotates with the pin tool. Lastly the surface striations will be shown to be caused by irregularities in the pin tool shoulder.

The “onion rings” seen in transverse weld cross sections have been recently studied by Krishnan <sup>2</sup> who showed that the onion rings appear as approximately circular bands in both lateral sections and in plan sections of the work piece. The bands curve away from the weld direction, and their spacing is the pitch (distance advanced/revolution) of the weld.

It has been suggested by Guerra<sup>3</sup> and Coronado<sup>4</sup> that the bands are layers of material that are transported by distinct and separate flows around the pin tool during welding. Distinct and separate flows with distinct and separate thermo-mechanical histories are necessary to give the alternating layers seen in these bands.

Guerra<sup>3</sup> and Coronado<sup>4</sup> have also noted that a faying surface copper foil tracer deforms into small particles that collect in a ring or “carousel” around the pin and appear in arcs in the wake of the weld. They have suggested that material is moved around the pin tool by both an extrusion or wiping of retreating side material and by material being shed from the rotating carousel. The carousel material falls off behind the pin tool in bulging cylindrical sheets interspersed with material that was wiped around the pin without entering the carousel. When viewed in cross section, these sheets appear as the onion rings.

radial component of the ring vortex flow may retain material in the carousel for multiple cycles around the pin. The vortex motion is apparently associated with weld quality because welds made with smooth pins or welds made with reversed rotation such that material is pulled upward by the threads typically shows voids.<sup>4</sup> This paper will interpret the “onion rings” as pieces of the carousel region that have been left behind the pin and that have been subjected to different thermo-mechanical processing.

## EXPERIMENTAL DETAILS

Welds were made on 0.25 inch (6.3mm) thick 6061 T6 aluminum using a Gorton Mastermill using a pin tool made from O-1 tool steel heat treated to Rockwell C hardness of 48. The nib or pin tool was 0.25 inches (6.3mm) in diameter and had standard 0.25/20 threads. The pin tool was rotated in a direction to push material downward. The shoulder was 0.75 inch (18.9mm) in diameter and cut perpendicular to the tool axis. Weld speeds varied from 2.3 in/minute (1mm/sec) to 6.9in/min (3mm/sec) and rotational speeds ranged from 300rpm to 900rpm. Welds were made at a constant plunge depth of 0.035 inches (.64mm) and the pin tool had a 1° lead angle.

Sizes of features were measured on metallographic samples cut from the welds and etched in Keller’s reagent. Samples were viewed on a Neophot microscope at approximately 20x. The sample stage was translated by micrometer mounts. Measurements were repeated five times and results were averaged.

Chemical inhomogeneities were probed using a FEI 515 SEM and an EDAX energy dispersive X-ray Fluorescence spectrometer.

## RESULTS AND DISCUSSION

### ONION RINGS

Fig. 2 is a sketch of a friction stir weld showing various features and directions that will be referred to. The direction X is to the side and perpendicular to what will be referred to as lateral sections. The direction Y is normal to the weld plate and perpendicular to what is referred to as plan sections parallel to the weld surface, and the well known “onion rings” are seen on a transverse section perpendicular to weld direction Z. Surface striations or tool marks are shown on the weld surface.

Fig. 3 shows a metallographic plan section at mid thickness from a sample in which the work piece was abruptly lowered during the weld leaving a hole in the work piece where the pin tool had been. A similar “unspinning” technique has been used by Colligan<sup>5</sup>. The faying surface is seen at the top of the figure and curls around the location of the pin in the direction of pin rotation. The metal clearly undergoes a large shear and apparently enters the carousel surrounding the pin tangentially. Similar structure has been observed around pins frozen in place by abruptly stopping the weld.<sup>8</sup>

The carousel surrounding the pin comes about as material ahead of the moving pin enters the zone of fast rotating material surrounding the pin and is highly deformed. The thickness of the annular carousel can be measured from the edge of the pin to the point where the faying surface is tangent to the zone. The outer diameter of this annulus will be referred to as the width of the carousel.

It is worthwhile to define another zone outside the carousel which will be called the “rotational zone”. The rotational zone around the pin has three parts: the deforming volume inside the carousel, the very high shear boundary of the carousel where the faying

surface suddenly disappears, and the deforming volume outside the carousel where the faying surface bends to a position approximately tangent to the carousel boundary. If the deformation inside and outside the carousel boundary were negligible, the velocity field inside the carousel would be approximately one of rigid body rotation about the pin, and the velocity field outside the boundary would be that of the work piece translation with respect to the pin.

The carousel region is very hot and recrystallization takes place almost immediately. The high temperature promotes flow in the regions inside and outside the carousel. Flow inside the carousel reduces the average rotational speed below that of a rigid body rotation. When temperature increases, for the same volume of metal to bypass the pin within the carousel, the boundary has to move out and the carousel width increase. But the entrained flow outside the carousel, which also carries some of the metal around the pin, broadens with temperature, and to some extent compensates for the loss of flow within the carousel. Both the outward displacement of the carousel boundary and the spreading of the entrained deformation outside the carousel should result in a widening of the rotational zone with temperature outside the pin.

To examine how the carousel changes in size with weld parameters a series of welds was made at different rotational velocities and different weld speeds and the width of the zone was measured. Fig. 4 shows that the carousel width increases as the weld becomes hotter either through higher rotational speed or slower weld velocity. Rada<sup>9</sup> treats the case of a moving point source of heat (the heat source in Friction Stir welding is, of course, more extended<sup>10</sup> but similar behavior would be expected) and shows that for a conductive metal such as aluminum, weld speed changes will make only small

differences in the temperature slightly ahead of the weld as is indicated by the small slopes in Fig. 4. Furthermore, changes in heat input (in this case, changes in rotational velocity) will not affect the change in temperature with velocity but only the absolute value of the temperature. This also is indicated by Fig. 4, which shows constant slopes for all rotational speeds.

Fig. 5 shows that the zero weld speed intercepts of these lines as a function of rotational speed form a straight line indicating linear increases in carousel diameter and temperature over this limited range of rotational speeds.

The relationship between the carousel width and the coarse bands seen on longitudinal and plan sections as well as the onion rings of transverse sections is not clear. Fig. 6 shows a polished plan section at mid thickness. Arc shaped bands are seen with spacing equal to the pitch of the weld as mentioned by Krishna.<sup>2</sup>

Although these bands can be seen at low magnification and even with the naked eye, it proved much more difficult to see them at higher magnification. Fig. 7 shows a higher magnification picture from near the center of Fig. 6. At this magnification the bands visible to the eye would be several centimeters apart. No such large bands could be found, but rather a much finer structure of recrystallized grains some of which form into occasional bands of small elongated grains as shown by the arrows in Fig. 7. These bands are irregular and have a spacing much less than a pitch. They are apparently regions of grain growth that take place in the already recrystallized material left behind by the weld. The bands visible to the naked eye, on the other hand, appear to be regions of material inclined slightly differently from the average surface so as to reflect light differently after etch. The difference in orientation would be consistent with the different



thermo-mechanical histories attributed above to different volumes in a friction stir weld bead. What is surprising is that differences in microstructure are so subtle. Either the thermo-mechanical processing differences at the pin-tool produce only small structural differences, or the high temperature in the wake of the weld smooths out these differences so completely that they are not readily seen.

The sample of Fig. 6 was repolished and examined in the SEM using energy dispersive X-ray fluorescence for chemical inhomogeneities (perhaps from the precipitate phases in the aluminum) associated with the large bands and none were found.

The width of the bands (or “path width”) in the wake of the weld (indicated by the arrow in Fig. 6) was measured under different weld conditions and is plotted in Fig. 4. The path width varies with weld temperature in the same way as the carousel width, but changes with rotational speed and weld speed are less in the case of the weld path. It is seen that the weld path is about 15% wider than the carousel width. The carousel is located near the center of the weld path but is displaced slightly towards the advancing side of the weld. The fact that the weld path is wider than the carousel and that the entire weld path has uniform fine recrystallized grains indicate that heavily deformed (otherwise it would not be recrystallized) material extends outside the carousel. The heavy deformation is characteristic of material that had at one time entered the carousel.

It is believed that the heavily deformed material extending beyond the carousel has been expelled from the carousel by the outward radial component of the ring vortex flow on the lower (anvil side) part of the pin. Note that the material added to the carousel at the top (shoulder side) of the pin by the inward radial component of the ring vortex flow cannot move down the pin forever, but must eventually reemerge in its now heavily

deformed and recrystallizing condition. After exiting the deformation flow field within the rapidly rotating carousel into the field of reduced deformation around the carousel, less hindered and more rapid recrystallization becomes possible. This difference in the rate of recrystallization is consistent with the different etching characteristics of the carousel and the material near it in Fig. 2. The bands seen in Fig. 6 are thought to be this material that has emerged out of the carousel with the radially outward component of the ring vortex and left behind the weld as the tool advances.

A quite interesting feature is seen in the plan section micrograph of Fig. 8 taken at mid-thickness near the edge of the weld path on the retreating side. The bands are seen on the left and an additional zone of recrystallized grains is seen outside the weld path. Finally, on the right side of the picture are seen grains of the parent metal. This region of recrystallized grains between the weld path and the parent metal does not exist on the advancing side of the weld path. It is thought that these grains were deformed sufficiently for recrystallization outside the carousel either in the flow wiped around the pin or in the ring vortex circulation. Toward the anvil the ring vortex flow is expected to turn radially outward and sweep the recrystallized zone further out. Fig. 9 shows that the size of this retreating side recrystallized zone increases toward the root of the weld consistent with the expectation.

## SURFACE STRIATIONS

The striations or tool marks that occur on the surface of the work piece have the same width as the shoulder. They are spaced a pitch apart but are not related to the interior striations that form the onion rings. The depth of the tool marks depends on the

condition of the pin tool shoulder. Fig. 10 shows lateral polished sections along the centerline of a weld made with: 1. a standard pin tool, 2. a standard pin tool polished with 800 grit paper along the edge of the shoulder, and 3. a polished pin tool cut along the edge by two approximately 0.7mm deep file gouges.

It can be seen that the tool marks consist of metal raised into a wavelike pattern that virtually disappears when the shoulder of the pin tool is polished. The tool marks are apparently made when an imperfection on the shoulder passes behind the pin tool and leaves behind a scratch. Since the tool is also advancing, the scratch has some undercutting to form the overhang of Fig. 10 bottom. The weld made with the polished shoulder (Fig. 10 middle) showed a smooth, and to the naked eye, featureless weld path. The weld made with the purposely damaged shoulder (Fig. 10 bottom) showed deep tool marks and had a very poor appearance. Although two defects were made at  $180^\circ$  from each other on the shoulder, the tool marks were still spaced a weld pitch apart so apparently the more severe of the two defects erased the effect of the other.

It is not known whether tool marks have more than cosmetic importance. They may be stress raisers and could be sites for preferential corrosion attack. In any case, it appears that their size can be controlled by attention to the condition of the shoulder.

## CONCLUSIONS

1. Two distinct currents of material around the pin tool with two distinct thermo-mechanical histories cause the well known "onion rings" seen in transverse Friction Stir Weld sections. In other sections, they appear as curved bands. They are caused by

surface suddenly disappears, and the deforming volume outside the carousel where the faying surface bends to a position approximately tangent to the carousel boundary. If the deformation inside and outside the carousel boundary were negligible, the velocity field inside the carousel would be approximately one of rigid body rotation about the pin, and the velocity field outside the boundary would be that of the work piece translation with respect to the pin.

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<sup>1</sup> Patent by The Welding Institute, International Patent Application No. PCT/GB92102203.

<sup>2</sup> Krishnan, K.N., "On the Formation of Onion Rings in Friction Stir Welds", *Materials Science and Engineering*, A327 (2002) 246-251.

<sup>3</sup> Guerra, M., McClure, J.C., Murr, L.M., *et al.* "Material Flow during Friction Stir Welding", *Proceedings Friction Stir Welding and Processing*, Editor K.V. Jata, M.W. Mahoney, R.S. Mishra, TMS (The Minerals, Metals and Materials Society), 2001.

<sup>4</sup> Coronado, E., McClure, J.C. Nunes, A.C., Murr, L.M., "Effect of Pin Tool Shape on Friction Stir Welds", *Proceedings Trends in Welding Conference*, ASM, Pine Mountain, Georgia, May 2002.

<sup>5</sup> Y. Sato, H. Kokawa, I. Keiske, E. Masatoshi, J. Shigetshi, and H. Takenori, "Microtexture in the Friction-Stir Weld of an Aluminum Alloy", *Metallurgical and Materials Transactions A*, Vol. 32A, April, 2001, p. 941-948.

<sup>6</sup> Nowak, B.M., Hall, A.C., Knorovsky, G.A., "High-Speed VideoFlow Visualization in Friction Stir Welds of Polycarbonate", *Proceedings 6<sup>th</sup> International Conference on Trends in Welding*, ASM, Pine Mountain, Georgia, April 2002.

<sup>7</sup> Colligan, K., "Material Flow Behavior during Friction Stir Welding of Aluminum", *Welding Journal*, July 1999, p. 229-s.

<sup>8</sup> Guerra, M., *Material Transport During Friction Stir Welding*, M.S. Thesis University of Texas El Paso, 2001.

<sup>9</sup> D. Radaj, *Heat Effects of Welding*, Springer-Verlag, 1992, p. 41.

<sup>10</sup> McClure, J.C., Tang, W., Murr, L.E., Guo, X., "A Thermal Model of Friction Stir Welding", *Proceedings of the 5th International Trends in Welding Conference*, ASM, Pine Mountain, Georgia, June, 1998, p. 590-595.

Carousel

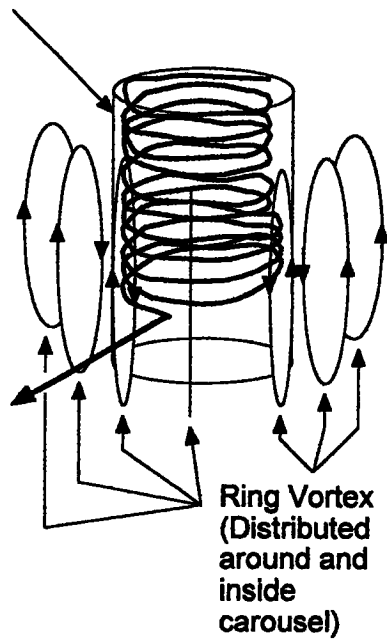


Fig. 1

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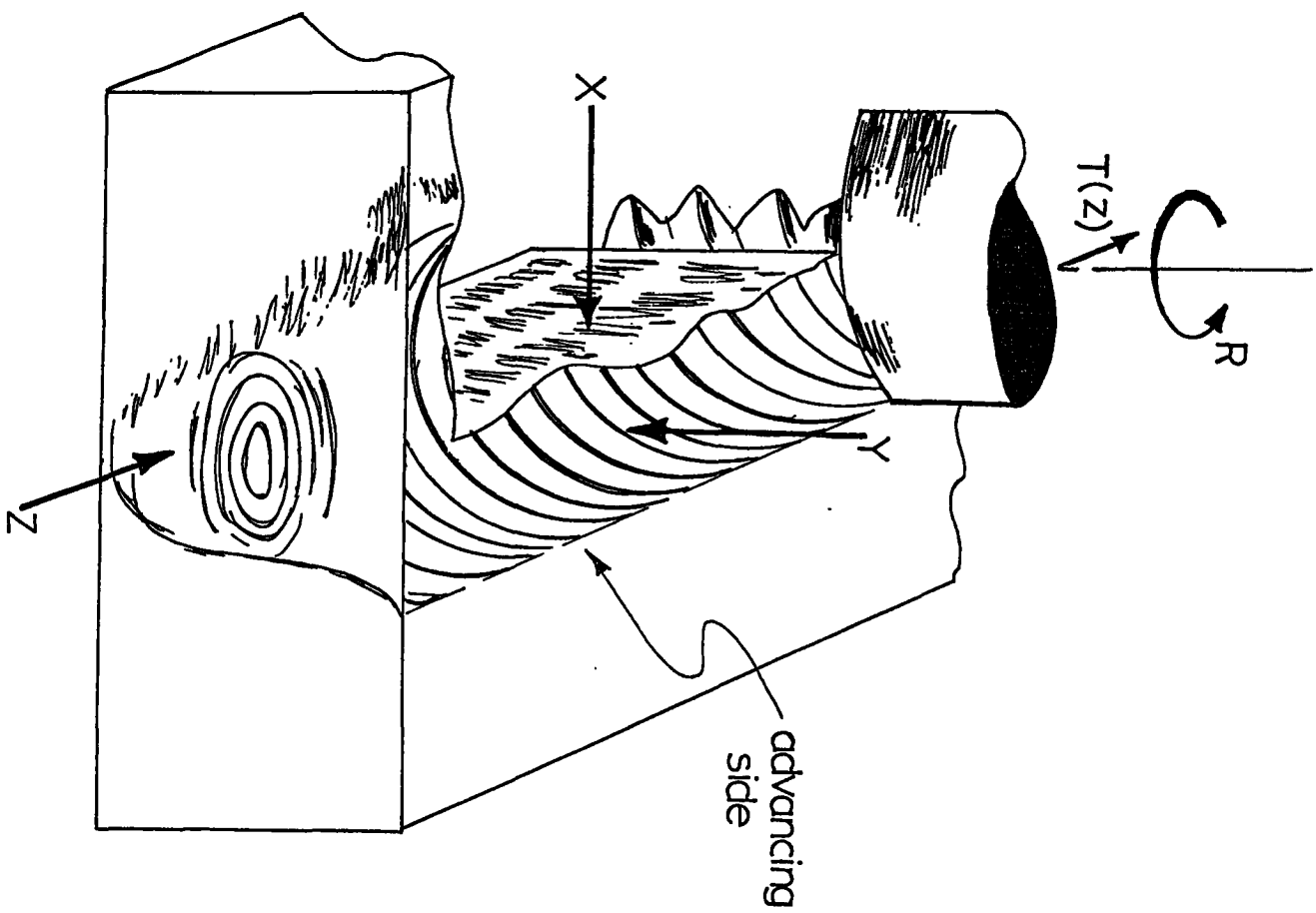
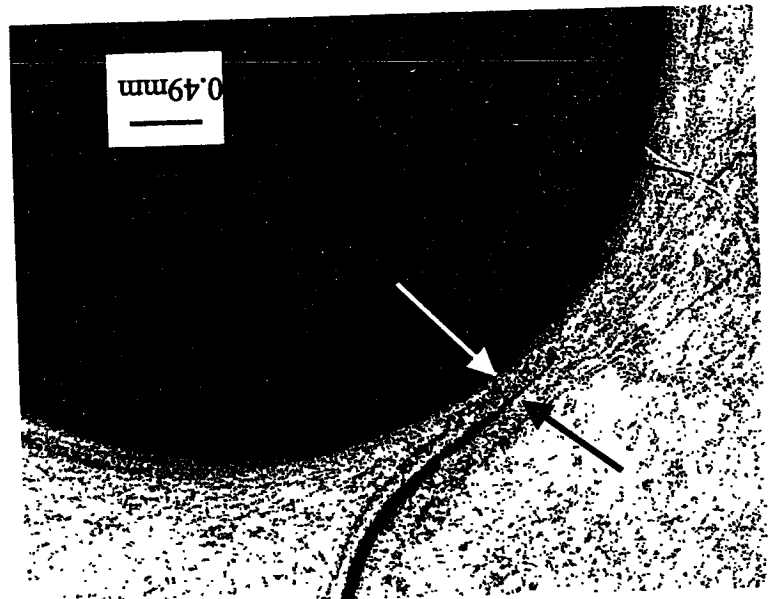


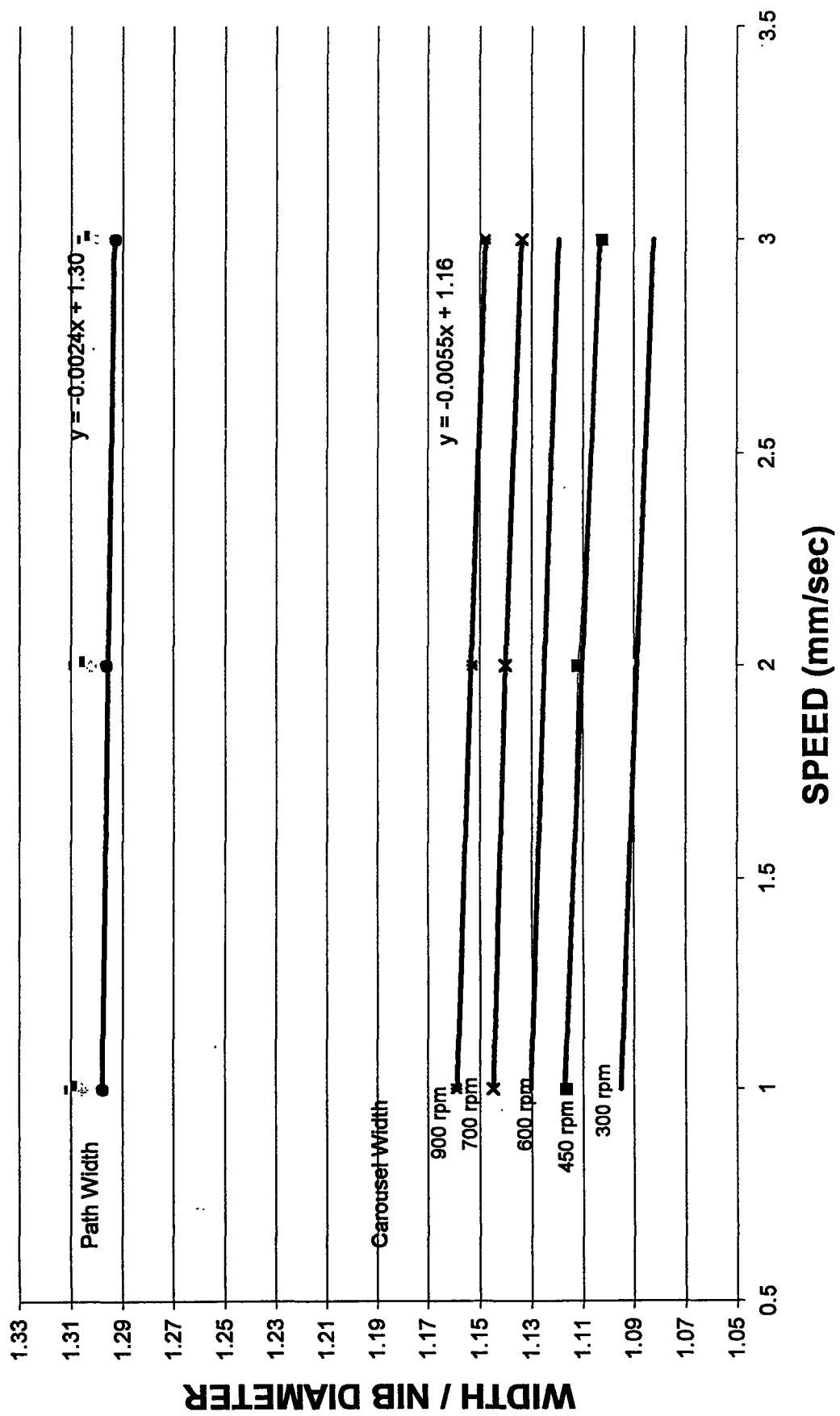
Fig. 2 2351

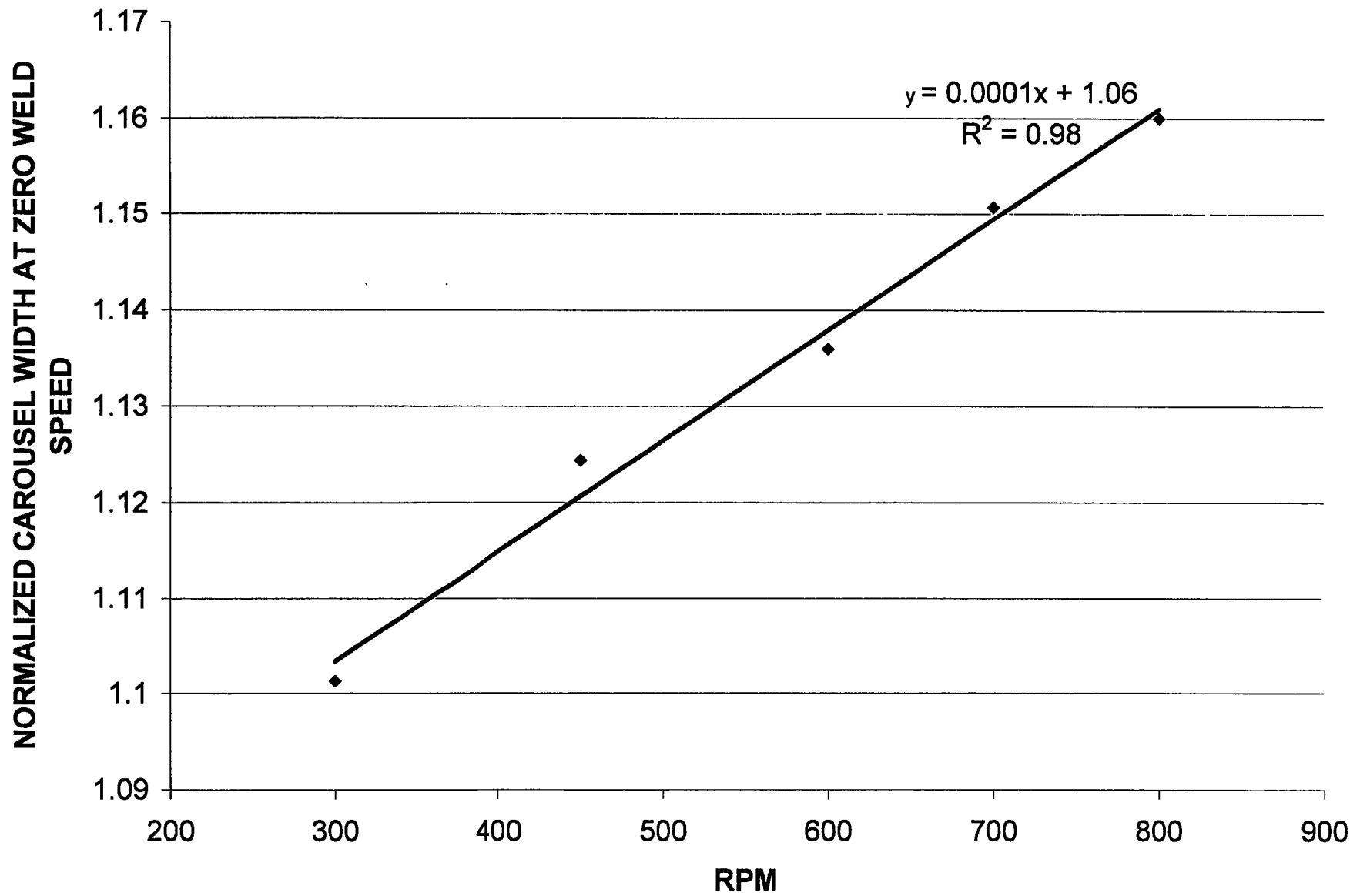
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8.4.5



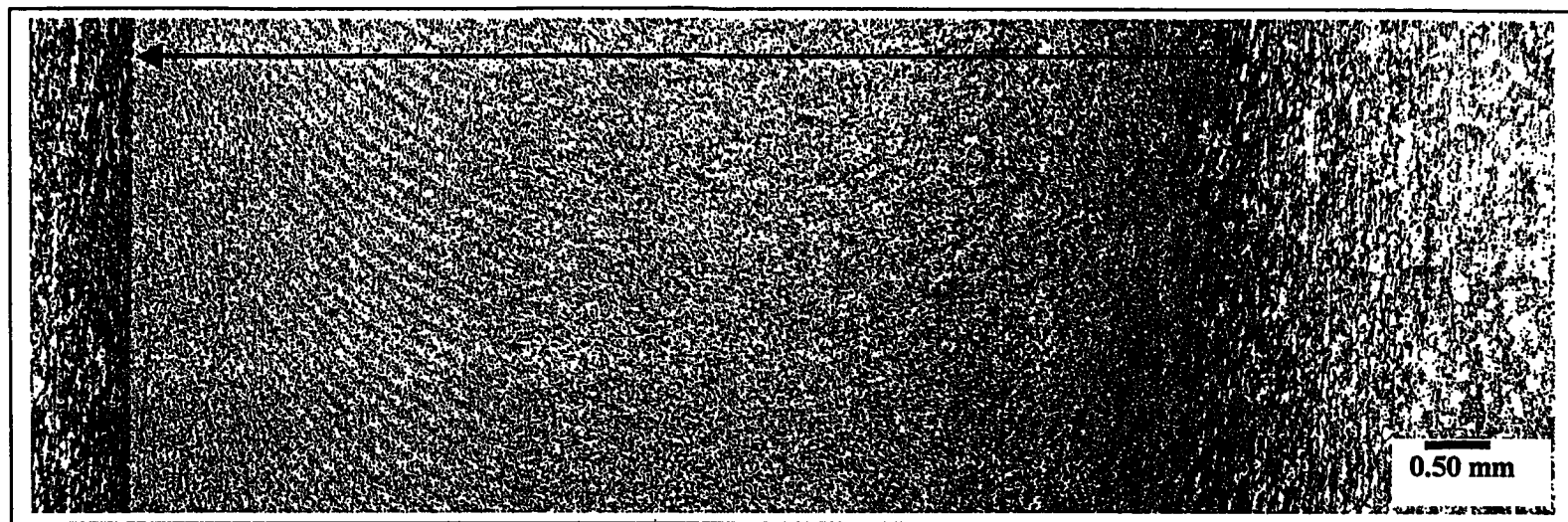






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Fig. 5

Fig. 6



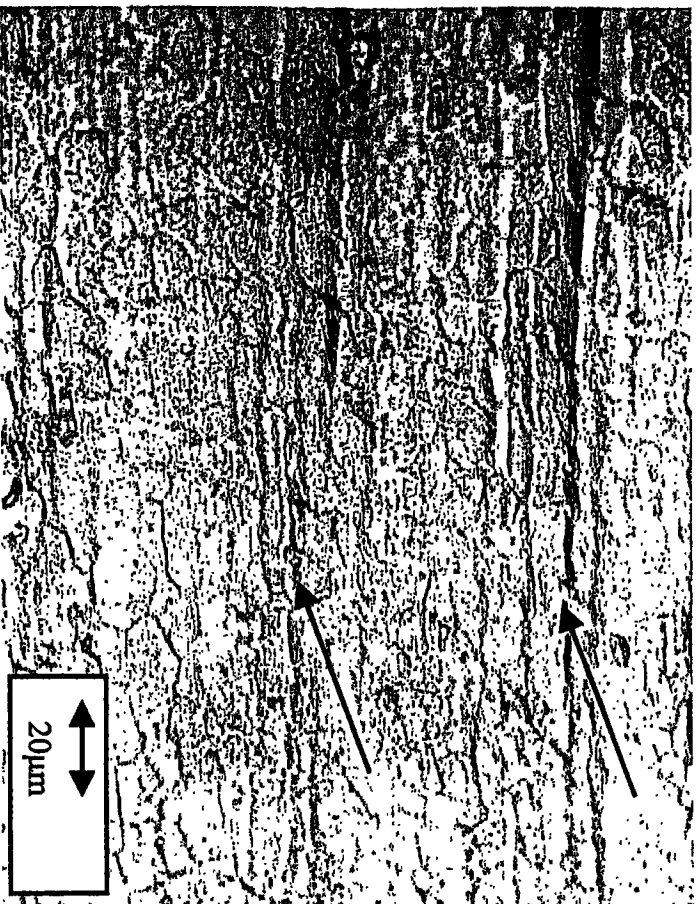
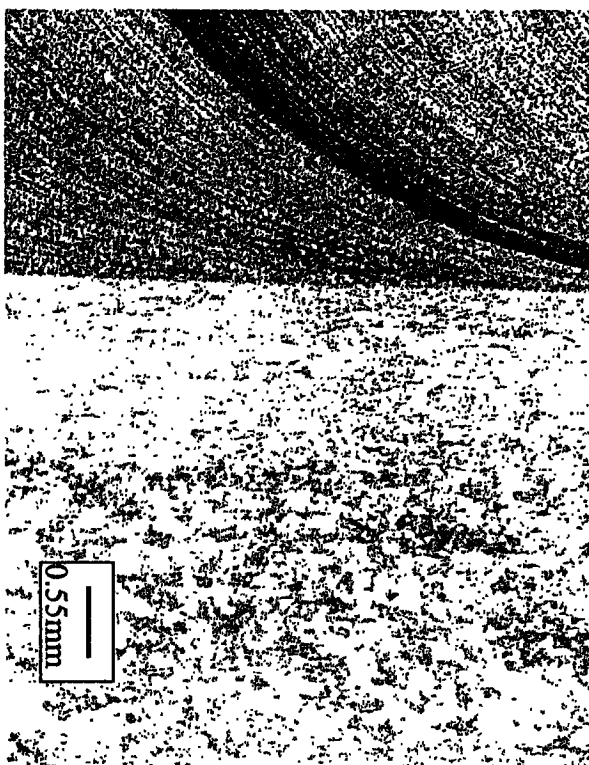
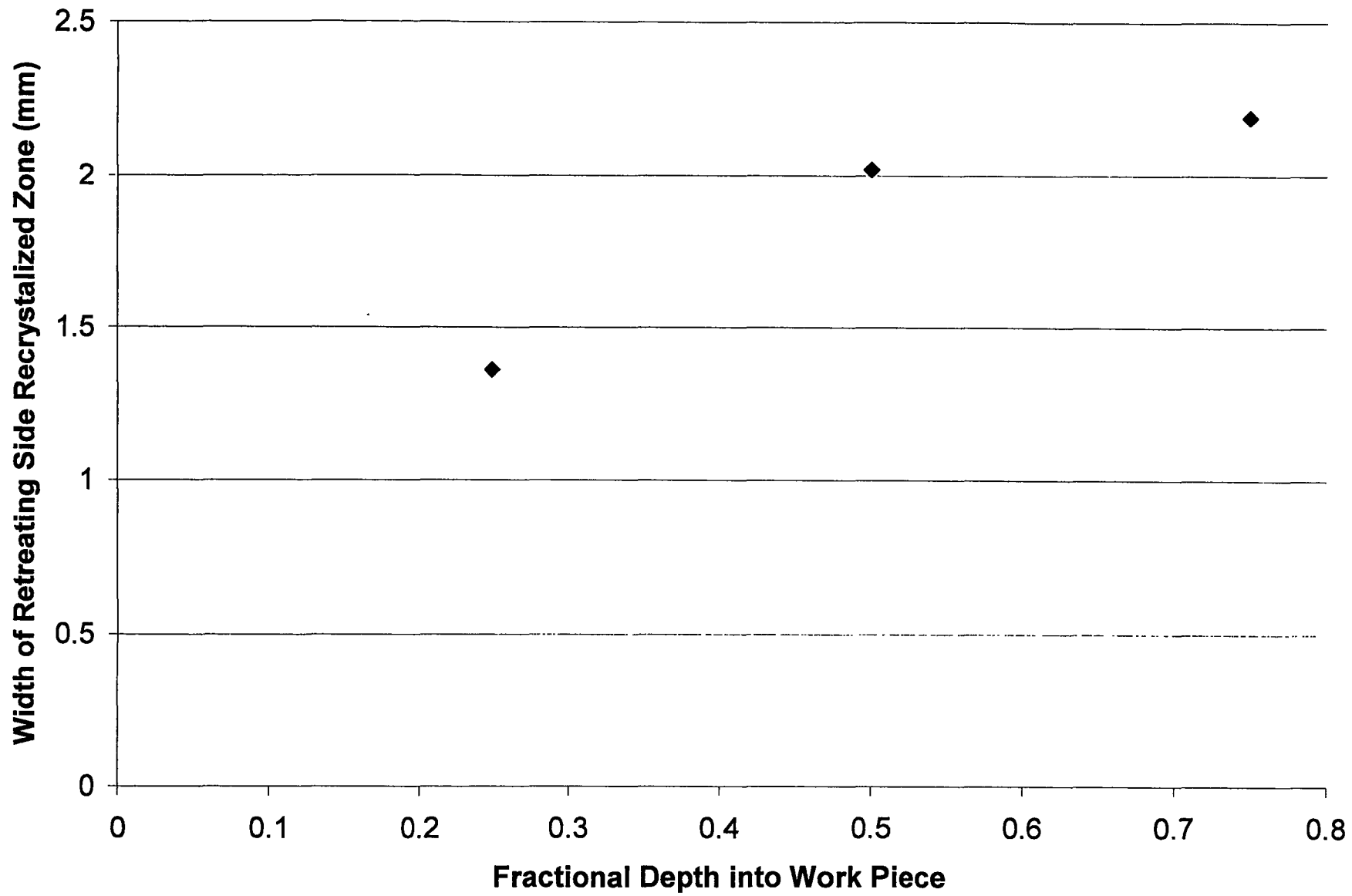
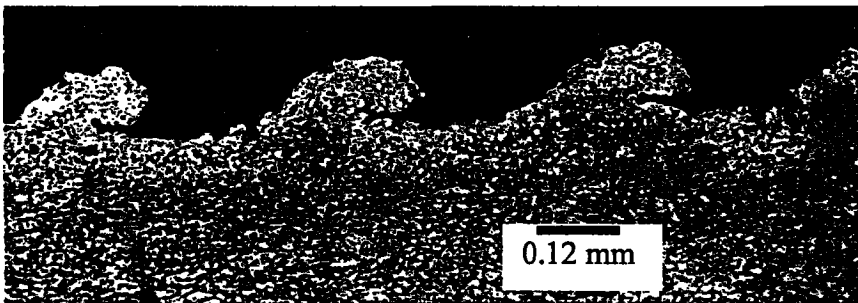
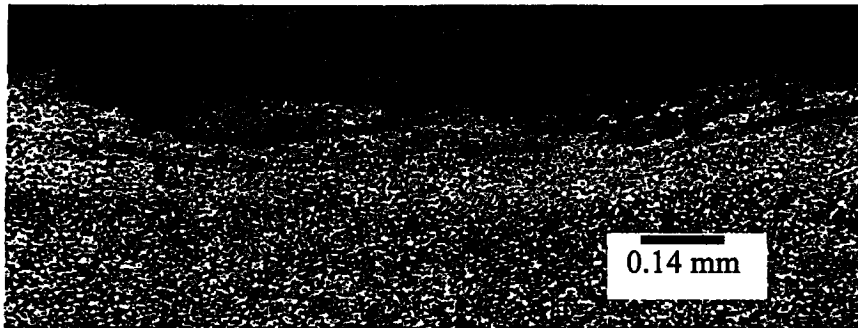


Fig. 7

10.8  
0.00







## CAPTIONS

Figure 1 Proposed flow fields showing the carousel and the ring vortex. A element of the work piece will follow the superposition of these flows.

Figure 2. Schematic of a Friction Stir Weld showing various sections. The lateral view is perpendicular to X, the plan view is perpendicular to Z, and the transverse section is perpendicular to Z. Note the "onion rings" on the transverse section and the surface striations or tool marks on the surface of the work piece.

Figure 3. Micrograph showing the faying surface curling around an unwound pin. The width of the carousel is the diameter of the annulus indicated by the arrows. The pin was proceeding upward in the picture and rotating counterclockwise. Note the carousel etches slightly darker than material just outside the carousel.

Figure 4. Normalized width of carousel and width of striations (path width) at mid thickness of sample as a function weld speed. The arrow in Figure 6 indicates the striation width that is plotted in this figure. Note that cooler welds (faster speed or lower rotational velocity) have smaller zones surrounding the pin.

Figure 5. Zero speed intercept of the carousel width from Fig. 4 for various rotational velocities. Note linear increase in width with rpm suggesting that temperature increases linearly (over this range) with rotational velocity.

Figure 6. Bands parallel to the surface at mid thickness. Weld speed was 2mm/sec and rotational speed was 650 rpm. Advancing side is on left. The bands are typically better defined on the advancing side. The arrow indicates the width of the striations or "path width" that was plotted in Fig. 4.

Figure 7. Higher magnification micrograph taken near center of Figure 6. Note small recrystallized grains with occasional rows of grains (indicated by arrows) that grew perpendicular the weld direction.

Figure 8. Micrograph from the retreating (right) side of Fig. 6. On left are bands, then a region of recrystallized grains and finally on the right are parent metal grains. It is thought that the recrystallized region outside the striations is material wiped around the pin on the retreating side or material that deformed in the ring vortex flow that never entered the carousel.



Fig. 9. Width of the retreating side recrystallized zone outside of the weld path at different depths into the sample. Weld speed was 2mm/sec and rotational velocity was 650 rpm.

Figure 10. Lateral views of the surface striations. The pin moved from right to left.  
Top: striations from a weld made with a typical machined pin tool.  
Middle: striations after shoulder of pin tool was polished.  
Bottom: striations after the shoulder of the pin tool was scratched in two places with a file.